Diocotron Instability in ELTRAP

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Electrostatic modes in the electron plasma confined in the Malmberg-Penning trap ELTRAP are investigated, analyzing the electric signals on the electrodes, and using the CCD diagnostics. In different experimental conditions, a well-defined mode (possibly, m=1 diocotron mode) is found, with frequency proportional to Q/B (Q is the total charge, B the magnetic field). The amplitude of the mode starts to increase at the beginning of the hold phase of the cycle, reaches a maximum, and then decreases to the background noise level. A decrease of the frequency corresponds to the decrease of the amplitude, indicating plasma loss to the wall. The observations point to a mode triggered by unstable density profile. A fast rise of the potential barrier easily excites the mode. Measurements performed with increasing ramp times show that the growth rate decreases, and at a long enough ramp time the instability does not arise.

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ANALYTICAL AND NUMERICAL STUDIES OF THE EVOLUTION OF PLASMA VORTICES USING A CONTOUR DYNAMICS APPROACH

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Due to the incompressibility of the particle density in a Penning trap, the dynamics of a plasma vortex of constant density can be studied by considering the evolution of its contour. Recently, the Authors developed a numerical technique, based on the image-charge method, that generalizes the classic contour dynamics method to systems having a circular boundary [1]. The high precision attainable with this technique provides reference results for the vortex dynamics, which represent a useful comparison for analytical theories.

In the present paper, three aspects connected with the contour dynamics of plasma vortices are discussed. In the first part, the **CIAO** code (**C**ontour Dynamics **I**mage-charge method for the **A**nalysis of **O**-boundary systems) is presented in some details. In particular, after describing the new methodology employed to calculate the velocity field, an algorithm for a proper treatment of the vortex contour is presented and its importance in order to obtain highly accurate results is discussed. Moreover, indications about the computational effort required by the code, along with comparisons with other numerical methods, are reported.

In the second part, the interaction of surface waves on a circular vortex with a point vortex in a Penning trap is studied analytically, so extending the theory developed by Lansky, O'Neil and Schecter [2] for an infinite domain. In addition, numerical results (obtained with the **CIAO** code) are reported for mergers that cannot be studied analytically [3]. These results confirm the effectiveness of the code even when long, thin filaments make the vortex contour very complicated.

Finally, a non-linear model to study the interaction of surface waves in the diocotron instability is developed. In this model, a semi-analytical, harmonic analysis of the contour of a perturbed plasma ring is considered. By taking into account second-order effects, one can describe the coupling mechanisms between contour modes, which cannot be predicted by a first-order analysis.

The analytical or semi-analytical models presented in second and third part of the work are based on the idea of describing a vortex only considering its contour. In general, the contour is described by means of a suitable set of parameters, that can either be a finite number of contour points (as in part I), or a finite number of Fourier coefficients (as in part II and III); the results provided by the theory are compared with the ones obtained with the **CIAO** code.

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Two-fluid model for the analysis of the m=1 diocotron instability

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The m=1 diocotron instability has been an open problem of non-neutral plasma physics for more than a decade. In fact, the classical two-dimensional drift-Poisson model is always stable with respect to m=1 perturbations, while experiments show a robust growth of the mode. In the last years, more complex models have been proposed [1-4], in order to provide a theoretical explanation of this growth. In the framework of the fluid models, the effect of the finite length of the plasma column has been studied [1,2], showing that the compressional mechanism induced by the non-uniformity of the plasma length can destabilize the m=1 mode. On the other hand, the spread in kinetic energy of the electrons produces a different penetration in the potential barrier for each particle and, consequently, a different $\mathbf{E}\times\mathbf{B}$ drift, thus breaking the fluid-like behavior of the plasma (as pointed out in [5]). In order to take into account all the above-mentioned effects, full kinetic models have been developed [3,4]; nevertheless, these models have proved to be rather difficult to be dealt with, both analytically and numerically. In the present work, the effect of the different electron energies is studied in a simplified way. The starting point is a simplified kinetic equation for the function $f(r,\theta,\varepsilon,t)$,

$$\frac{\partial f}{\partial t}+\alpha(\varepsilon)\frac{\mathbf{e}_z\times\nabla\phi}{B_0}\cdot\nabla f=0 \tag{1}$$

being $\varepsilon=\frac{1}{2}mv_z^{\;2}-e\phi$; $\alpha(\varepsilon)$ is a suitable function of the electron axial energy ε, accounting for the different penetration depth. By using a first-order Legendre polynomial approximation, the following two-fluid model is obtained:

$$\begin{cases}\dfrac{\partial n_1}{\partial t}+\langle\alpha\rangle(1-\mu)\dfrac{\mathbf{e}_z\times\nabla\phi}{B_0}\cdot\nabla n_1=0\\[2ex]\dfrac{\partial n_2}{\partial t}+\langle\alpha\rangle(1+\mu)\dfrac{\mathbf{e}_z\times\nabla\phi}{B_0}\cdot\nabla n_2=0\\[2ex]\nabla^2\phi=\dfrac{e}{\varepsilon_0}(n_1+n_2)\end{cases} \tag{2}$$

where the coefficients $\langle\alpha\rangle$ and μ are calculated self-consistently from the full kinetic model [4]. The densities n_1 and n_2 account for the different energies of the particles. The linear analysis of Eq. (2) shows that the m=1 mode becomes unstable, with a growth rate proportional to μ (the effect is less relevant for higher modes). Numerical simulations have also been performed; results will be presented at the Workshop.

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THE CIAO CODE: CONTOUR DYNAMICS, IMAGE-CHARGE METHOD FOR THE ANALYSIS OF O-BOUNDARY SYSTEMS

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The contour dynamics (CD) is a method originally developed to study inviscid, two-dimensional flow in an infinite domain [1, 2]. The CD technique is suitable for very accurate studies of the contour evolution for regions of constant vorticity. By resorting to the fact that the Green function of the Poisson equation in an infinite domain, $G(\mathbf{r}'\rightarrow\mathbf{r})$, is a function only of $|\mathbf{r}'-\mathbf{r}|$, the classic CD method expresses the velocity on each vortex contour analytically, in terms of line integrals on the contours themselves. In this way, no computational grid is required and, consequently, high precision can be attained in the simulations. The contour dynamics approach cannot be immediately extended to bounded systems, and, in particular, to systems with a cylindrical boundary (i.e., the case of interest to study non-neutral plasmas confined in a Penning trap), in which the corresponding Green function satisfies no longer the above-mentioned property. Fajans *et Al.* proposed a solution [3], by using a suitable Fourier expansion to calculate the electric potential due to the circular electrode; following this approach, the precision of the solution depends on the number of the Fourier coefficient used for the potential. A new technique has been proposed by the Authors [4] to overcome this difficulty by making use of the image-charge method: the presence of the circular electrode is taken into account by introducing of a suitable image-charge distribution in an infinite domain. In this way, the velocity field on the contour of the real vortex is evaluated analytically as a sum of line integrals on both the real and the image contour. The new methodology has been included in the **CIAO** (**C**ontour dynamics, **I**mage-charge method for the **A**nalysis *of* **O**-boundary systems) simulation code. Within the **CIAO** code, the contour of each vortex is approximated with a polygonal line. A proper redistribution routine operates during the simulation, to maintain the desired accuracy by varying locally the number of contour points when needed. As the contour becomes increasingly complex during the evolution, new points on the contour are added. To show the effectiveness of the methods, simulations concerning classic phenomena (in particular, the diocotron instability and the interaction of vortices) will be presented.

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LINEAR AND NON-LINEAR INTERACTION OF PLASMA VORTICES

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As the velocity field due to the $\mathbf{E}\times\mathbf{B}$ drift is solenoidal, the dynamics of regions of constant charge density (vortices) in a Penning trap can be studied by considering the evolution of their contours.
In the present work, this idea is employed to study two different kinds of phenomena. The first analysis concerns the interaction between a finite-size vortex (of constant charge density and placed in the center of the trap) and a weak, pointlike vortex. By using a proper harmonic representation of the contour of the finite vortex, a linear model for the Fourier coefficients of the surface waves is deduced, allowing one to describe the interactions between the two vortices when small surface waves are induced. The resonance condition between the surface modes and the point vortex, along with a sufficient condition for the merger not to occur, is obtained, so generalizing the results obtained by O'Neil *et Al.* [1] for an infinite domain.
The second study concerns the non-linear interaction of surface modes in a plasma ring. Starting from the equations governing the evolution of the outer and inner contours (derived by supposing the charge density to be constant within the ring), a second-order model (with respect to the surface-wave amplitudes) is developed, in which the coupling-mode coefficients, determined in a fully analytical way, are evaluated numerically. The results presented concern mainly the non-linear excitation of linearly-instable diocotron modes by means of one or a couple of linearly-stable modes. These non-linear effects can become relevant, for instance, when studying the evolution of the azimuthal m=1 diocotron mode. The couplings between modes cannot be described within the framework of a classic, first-order analysis of stability and, for this reason, their semi-analytical evaluation represents an innovative aspect in the study of the dynamics of the non-neutral plasmas dynamics.
The validity of all the results presented has been checked by means of a non-linear contour dynamics code developed by the Authors [2].

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Damping of Trivelpiece-Gould Modes in Trapped Non-Neutral Plasmas *

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Collisionless damping of standing plasma waves is characterized from ultra-low amplitude thermal excitations to large amplitudes where particle trapping dominates. Quantitative measurements of "linear Landau damping" and "nonlinear wave-particle trapping oscillations" of $m_\theta = 0$ Trivelpiece-Gould (T-G) modes in a trapped pure-electron plasma are discussed and compared to theory.

At low wave amplitudes ($\delta n/n_0 < 10^{-3}$), the measured linear damping rate ($10^{-3} < \gamma_{\rm L}/\omega < 10^{-1}$) agrees quantitatively with Landau damping theory over a range of plasma temperatures ($1 < {\rm T}_e < 3$ eV, $3 < v_\phi/\bar{v} < 5$). To demonstrate the Landau nature of the damping, we eject electrons with high parallel velocity, effectively obtaining a truncated velocity distribution function. When the truncated velocity approaches the wave phase velocity, the observed damping decreases precipitously, verifying that the damping is caused by resonant electrons.

For larger excited amplitudes ($10^{-3} < \delta n/n_0 < 10^{-2}$), the wave initially damps at the Landau rate, then re-grows and oscillates in amplitude, approaching a BGK state. This is because the wave-resonant particles become trapped in the wave potential, sloshing with frequency $\omega_T = \sqrt{eE_z k_z/m}$, as first analyzed by O'Neil in 1965. The measured times characterizing the first bounce oscillation are found to agree quantitatively (to about 20%) with predictions based on a self-consistent numerical calculation of the wave trapping process.

A separate residual damping of $10^{-5} \leq \gamma/\omega \leq 10^{-3}$ is observed in temperature and amplitude regimes where Landau damping is negligible. Measurements and theory show that this residual damping is proportional to the input resitance of the receiving amplifier and the plasma antenna coupling coefficient.

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Flat-top Conundrum[1]

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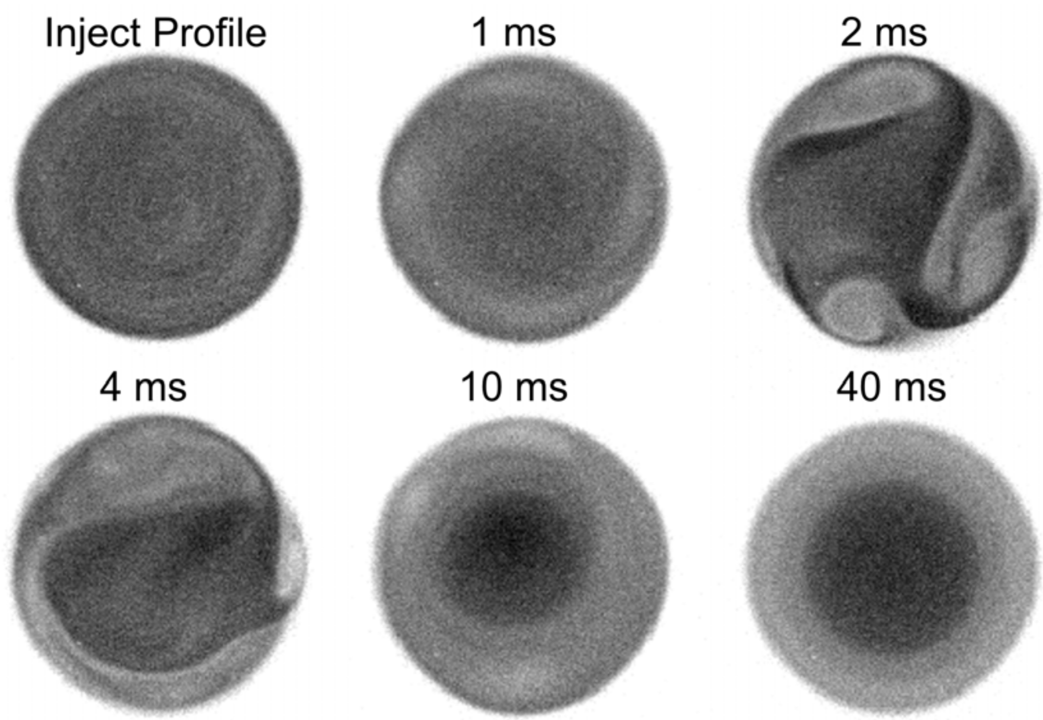
A truism of non-neutral plasma physics research is that flat-top (i.e. $n(r) = \text{const}$ for $r < r_p$, $n(r) = 0$ elsewhere) plasmas are stable. However, experiments on Berkeley's photocathode machine clearly show that flat-topped plasmas are violently unstable; after several column rotations the plasmas relax to slope-shouldered distribution whose central density is higher than the initial density. As this result cannot be due to Euler dynamics, some new physics must be involved. One possibility is that end effects are driving the instability, however, the plasmas are relatively long with relatively flat ends and this possibility seems unlikely. Recent computer simulations by Gorgadze et. al indicate the plasmas are very non-Maxwellian. A likely explanation is a non-axisymmetric two-stream instability.



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Autoresonant Control of Vortices by Coupling to External Oscillations

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The autoresonance (adiabatic nonlinear phase locking) in systems of coupled waves and oscillations with slow parameters has been investigated previously [1,2]. Generally, one can efficiently exchange energy between different degrees of freedom by slow passage through resonances in these systems. Here we use similar ideas for controlling vortices (magnetized non-neutral plasmas) by coupling to external non-dissipative circuits with slowly varying parameters. We show that a large amplitude l=1 diocotron mode can be efficiently controlled by this approach. In particular, the coupled system enters phase locked evolution stage provided the chirp rate of parameters of the circuit is below a threshold. In such a case, the amplitude of the diocotron mode self-adjusts to stay in resonance with the circuit and becomes a simple function of the time varying external frequency. Previously, l=1 diocotron mode was controlled by applying a perturbation having a slowly varying frequency, but the approach required starting from an unexcited mode. Coupling to an external circuit yields an extension of autoresonant control idea to arbitrary initial mode amplitudes. A similar approach allows control of a vortex pair. In contrast to l=1 diocotron mode, where the amplitude can only be increased from its initial value, the distance between vorticies in the vortex pair can be either decreased or increased depending on its initial value. We also find that sufficiently weak dissipation does not destroy autoresonance in these coupled systems.

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The ion cyclotron resonance frequency as a space-charge probe of trapped electrons

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In the process of studying poly-anionic species [1] the cyclotron frequency of anions stored simultaneously with an electron ensemble in the Cluster Trap (a Penning trap for metal cluster research [2]) has been investigated.
After in-flight capture of the metal clusters the electrons are created by electron impact ionization of argon gas pulses inside the trap volume. The ions are detected and analyzed by axial extraction into a drift section for time-of-flight mass spectrometry. The clusters' (reduced) ion cyclotron frequency is probed by dipolar radial excitation and monitoring the number of clusters as a function of excitation frequency. In resonance, the ions are ejected from the trap volume which leads to a drop of the ion signal.

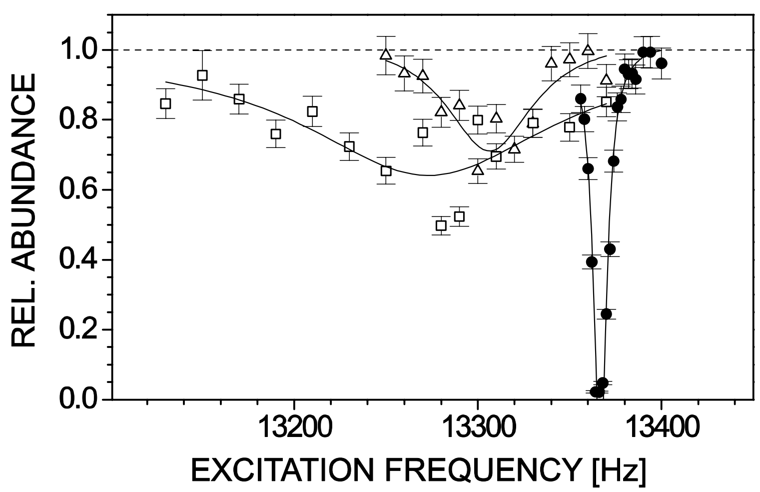

Fig.1: Relative abundance of gold clusters Au_{27}^{1-} as a function of the dipole excitation frequency for parameters of electron production inside of the Penning trap.

When the number of stored electrons is varied (e.g. by an increase of the number of argon gas pulses applied to the trap volume), a shift of the ions' cyclotron frequency is observed (see Fig.1). In addition, the resonance curves show an increased width.
These preliminary results suggest that the ion cyclotron resonance frequency may be used to monitor the space charge density of the trapped electron ensemble.

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Trapped-Particle Diocotron Modes

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Recent experiments have characterized trapped-particle modes on a nonneutral plasma column [1], and this paper presents a theoretical model of the modes. Theoretical predictions for the mode frequency, damping rate, and eigenmode structure are compared to experimental observation. The modes are excited on a nonneutral plasma column in which classes of trapped and passing particles have been created by the application of a potential barrier. The column resides in a Malmberg-Penning trap, and the barrier is created by applying a voltage to an azimuthally symmetric section of the wall near the axial mid-point of the column. Low energy particles near the edge of the column (where the barrier is strong) are trapped in one end or the other, while high energy particles near the center of the column transit the entire length. The modes have azimuthal variation $\ell = 1, 2, ...$ and odd z-symmetry. The trapped particles on either side of the barrier execute $\mathbf{E}\times\mathbf{B}$ drift oscillations producing density perturbations that are 180° out of phase with each other, while passing particles run back and forth along the field lines attempting to Debye shield the perturbed charge density. The mode is damped by collisional scattering across the separatrix between trapped and passing particles. The damping rate is calculated using a boundary layer analysis of the Fokker-Planck equation. It is also shown that the damping is associated with radial transport of plasma particles.

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Asymmetry-Induced Damping of Diocotron Modes

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The nominally stable electron plasma diocotron modes ($k_z = 0,\ \ m = 1, 2, ...$) exhibit strong exponential damping when the confinement fields have weak θ-asymmetries and z-variations. This damping is due to collisional dissipation at the velocity-space separatrix between axially trapped and passing electrons, and is intimately related to the previously-studied damping of the "trapped particle modes" and bulk plasma expansion [1]. This may also be viewed as collisional dissipation of the asymmetry-induced "sloshing currents."

We find that the damping rate γ_m of the diocotron mode with frequency f_m exhibits robust scaling of $\gamma_m/f_m = -\nu_P/S$, where $\nu_P \equiv \dot{P}_\theta/P_\theta$ is the rate of plasma expansion, and S is a dimensional factor depending only on the type of the trapping separatrix. This scaling is observed for a wide range of plasma parameters, for various asymmetry types and strengths, and for both collisional and stimulated separatrix crossings.

This damping mechanism dominates for weak electron-electron collisionality $\nu_{\rm ee}$, because it scales as $\gamma_m \propto (\nu_{\rm ee}/f_m)^{1/2}$. This unusual scaling arises because arbitrarily small velocity scatterings near the separatrix can cause a dissipative trapped-to-passing transition. In contrast, mode damping due to "rotational pumping" requires bulk perp-to-parallel velocity scatterings, giving a scaling $\gamma_{\rm rp} \propto \nu_{\rm ee}^1$ [2]. Thus, this "asymmetry plus separatrix" damping may explain the damping previously observed at low densities and low $\nu_{\rm ee}$ [3].

This damping is most noticeable at low magnetic fields, because the $\nu_P \propto B^{-2}$ scaling implies $\gamma_m \propto B^{-3}$. Thus, it may provide the explanation for the anomalous diocotron decay observed in prior experiments at low magnetic fields [4].

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Diocotron Instabilities in an Electron Column Induced by a Small Fraction of Transient Positive Ions

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The addition of a small fraction of transient positive ions (mostly $H_2{}^+$) to an otherwise stable pure electron plasma column results in an instability of diocotron modes ($k_z = 0, \quad m = 1, 2, 3...$). We study these instabilities far away from the previously studied resonance between the diocotron waves and radial ion orbital motion [1,2]. The fraction of transient positive ions is maintained either by continuous external injection of ions ($i_+ \sim 0.2$–20 pA), or by ionization of the background gas in hot plasmas ($P_{H2} = 0.3$–30 nTorr, $T_e = 7$–9 eV). For injected ions, we define the equivalent "ionization rate" per electron as $\nu_+ = i_+/Q_e$, where $Q_e \equiv eN_L L_p$ is the total charge of the electron column. In both cases, the observed *exponential growth* rate γ_m is *directly proportional* to the ionization rate ν_+ (or to the current of positive ions) with corresponding coefficients κ_m *much greater than one,* i.e., $\gamma_m = \kappa_m \nu_+$, where $\kappa_m \sim 10^1$–10^3.

These characteristics differ totally from existing theories of ion-induced instabilities, both for the cases of trapped [1] and transient ions [2]. Theory suggests that the ion moves around a fixed point in the $m = 1$ diocotron frame, and this point is displaced *outward* from the center of the electron column by a small ($\sim r_p^4/\lambda$) fraction of the diocotron mode amplitude [2]. Here, $r_p \equiv R_p/R_w$ is the electron column radius, and the ion magnetization parameter is $\lambda \equiv B^2/2\pi n_e m_i c^2 \gg 1$. An ion wobbling around this fixed point causes an exponential growth of the diocotron mode [2], with predicted rate $\gamma_1^{\rm th} \approx (r_p^4/\lambda)\nu_+$. For the range of our experiments, $10^{-5} \le r_p^4/\lambda \le 10^{-2}$, so the theory underestimates the growth rate by many orders of magnitude. This indicates clearly that as yet unspecified effects play a dominant role in ion motion.

The observed values $\kappa_m \gg 1$ imply that the average change $\langle \delta r_+^2 \rangle$ in the mean-square-radius of the ions during their residence in the electron plasma exceeds the amplitude d of the diocotron mode by many orders of magnitude, i.e. $\langle \delta r_+^2 \rangle = 2\kappa_m d^2$. This effect may have strong implications for the anti-hydrogen creation technique of propelling anti-protons through trapped e^+ clouds.

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Damping of Trapped-Particle Asymmetry Modes in Non-Neutral Plasma Columns

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Abstract: Asymmetry modes ($m=1$, $k_z \neq 0$) are diocotron-like modes in finite-length plasma columns in Malmberg-Penning traps. The simplest such mode has been reported by Kabantsev *et al.* to exhibit strong exponential damping for which the damping constant scales as $B^{-0.5}$ for sufficiently strong magnetic fields. Hilsabeck and O'Neil have reported theoretical success in accounting for features of the data by ascribing the damping mechanism to velocity scattering of marginally trapped particles. We have investigated the modes with a detailed 3-d particle-in-cell (PIC) drift-kinetic computer simulation. Although PIC simulations do not employ realistic collisions, the simulations in this case also reproduce many of the salient features of the data, including the drift-related B^{-1} dependence of the mode frequencies and the $B^{-0.5}$ dependence of the damping constant. In the simulations particle transport associated with the damping is seen not to be a direct collisional effect, but rather a feature of orbital dynamics associated with transitions from trapped-to-untrapped or untrapped-to-trapped state relative to the inversion plane of the asymmetry. We have used the simulations to investigate the modes at small seed amplitudes and observe linear flattening in the mode frequency as the seed amplitude becomes small. In contrast, the decay constant does not flatten as the seed amplitude becomes small, indicating a nonlinearity in its behavior. We also describe efforts to account for the $B^{-0.5}$ scaling of the decay constant.

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2003 Workshop on Non-Neutral Plasmas

Sorting Category: Experimental

Examination of m=1 Diocotron Mode Growth at Low Electron Densities* STEPHEN F. PAUL, KYLE MORRISON, RONALD C. DAVIDSON Princeton Plasma Physics Laboratory — Previous experiments on the Electron Diffusion Gauge have shown that the diocotron mode is strongly damped at higher neutral pressures. In addition, the plasma expansion and the mode growth were seen to depend oppositely on electron density and neutral pressure; diocotron modes were damped at higher densities and expansion increased with density. However, drag exerted on the rotating plasma by collisions with neutrals is predicted to excite the mode. To resolve this discrepancy, experiments have been conducted to examine the coupling between plasma expansion and the m=1 diocotron mode, and have revealed several interesting phenomena: 1) The plasma expansion rate is not affected by resistively driven diocotron mode growth, even for high growth rates. 2) Diocotron mode growth rates are observed to be strongly dependent on filament conditions. (Mode growth rates of nearly 20 $\sec^{-1}$ have been observed with negligible resistive drive.) Specifically, in a narrow range of filament bias voltages that correspond to low electron densities, the mode growth is very sensitive to the heating voltage across the filament. This occurs despite the fact that the variation in heating voltage barely affects the plasma expansion, the plasma density profile, the filament emission current, or the total number of electrons in the plasma. 3) At high filament heating voltages ($V_h > 6V$) and low neutral pressures ($P < 10^{-9}$ Torr), the growth rate is seen to increase with neutral pressure, oppositely to that seen previously. This scaling is consistent with the theoretical analysis of diocotron mode growth, though it occurs with a much higher magnitude.

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Prefer Poster Session
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Observation of Resonant and Non-Resonant Thermal Fluctuations in Pure Electron Plasmas

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Thermally excited plasma modes are observed in near-equilibrium pure electron plasmas. When the mode is weakly damped, the measured emission spectrum [1] is a simple Lorentzian of width γ at the $(m_z = 1, \;\; m_\theta = 0)$ Trivelpiece-Gould mode frequency ω_0. The measured spectrum together with a plasma-antenna coupling calibration uniquely determines the plasma temperature. This coupling calibration can be obtained directly from the received spectrum when the receiver-generated noise absorbed by the plasma is significant; or from separate wave transmission/reflection/absorption measurements; or from kinetic theory calculations. This non-destructive temperature diagnostic agrees well with the standard dump diagnostic. In this weakly damped regime, Debye shielding strongly suppresses the non-resonant fluctuations, so off-resonant fluctuations are not observable.

In the strongly damped mode regime (i.e. high temperatures), the non-resonant fluctuations increase to detectable levels. Preliminary measurements show a broad, flat spectrum below the mode, but no additional fluctuations above ω_0. For example, when $\gamma/\omega_0 \sim 0.07$, the non-resonant fluctuation amplitude at $\omega_0 - 3\gamma$ is about 30% of the resonant peak amplitude, whereas the Lorentzian extends down to 10% of the peak amplitude at $\omega_0 + 3\gamma$ with no significant non-resonant signature. These measurements are qualitatively consistent with ab-initio theory calculations which include Debye shielding.

This work is supported by National Science Foundation grant PHY-9876999 and Office of Naval Research Grant N00014-96-1-0239.

[1] F. Anderegg, N. Shiga, D.H.E. Dubin, C.F. Driscoll, and R.W. Gould, Phys. Plasmas **10**, 1556 (2003).

Numerical Study of Diocotron Instability with MDGRAPE-2

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The diocotron instability in a low-density nonneutral electron plasma is examined via two-dimensional numerical simulations. It is well known that in two-dimensional case the equation of motion of low-density nonneutral plasmas with the guiding center approximation coincides with the Euler equation. In this work, the vortex method is used in the simulations.

The vortex method needs the Biot-Savart integral to determine a flow velocity from the (point) vortices. Unfortunately, it takes a considerable time to calculate the Biot-Savart integral in simulations. Thus, a special-purpose computer, MDGRAPE-2, is used to accelerate the calculations of the Biot-Savart integral in the simulations. It should be mentioned that MDGRAPE-2 was originally designed for molecular dynamics simulations to accelerate calculations of Coulomb force, Van der Waals force and so on.

As a first step of this work, accuracy of the simulations is verified qualitatively and quantitatively. The diocotron modes observed in the simulations agree with the results predicted by the linear theory. The growth rates of the linearly most unstable modes also agree with the theoretical ones. This implies that MDGRAPE-2 gives sufficiently accurate results for the vortex method.

As a second step, simulations of time evolution of two circular clumps are carried out to investigate a mechanism how the electron clumps merge. The two circular clumps without a conducting wall surrounding the electrons move like binary stars if the motion of the clumps is restricted in a two-dimensional plane. However, under the presence of the conducting wall, the two clumps merge. The merging properties of the clumps strongly depend on the radius of the conducting wall. It is concluded that the electric field induced by the conducting wall makes the nonlinear growth stage of the diocotron instability unstable and has the clumps merge.

Abstract Submitted
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Sorting Category: Experimental

Measurements of Plasma Expansion due to Background Gas in the Electron Diffusion Gauge Device[1] KYLE MORRISON, STEPHEN PAUL, RONALD DAVIDSON Princeton Plasma Physics Laboratory — The expansion of the Electron Diffusion Gauge (EDG) pure-electron plasma due to collisions with background neutral gas atoms is observed. The EDG device is a Malmberg-Penning trap with diagnostics to measure the axially-integrated, 2-D density profile, the plasma's total charge, the on-axis electron temperature, and the evolution of the $m = 1$ diocotron mode. The expansion rate at high-vacuum pressures is found to be in agreement with the classical fluid estimate

$$\frac{d}{dt}\langle r^2\rangle = \frac{2N_L e^2 \nu_{\rm en}}{m\omega_c^2}\left(1 + \frac{2T}{N_L e^2}\right),$$

where N_L is the plasma line density, T is the homogeneous plasma temperature (in eV), ω_c is the electron cyclotron frequency, and $\nu_{\rm en}$ is the electron-neutral atom collision frequency.

Measurements of the expansion rates made with the new, 2-D density diagnostic suggest that the rates measured previously were observed during the plasma's relaxation to quasi-equilibrium, making it even more remarkable that they scale properly with pressure. The implications of changes in the plasma temperature for our understanding of the expansion are also investigated.

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Prefer Poster Session
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Non-Neutral Plasma Cooling Using Buffer Gas Collisions

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We will describe efforts to cool pure-electron plasmas using inelastic collisions with a room temperature buffer gas. In the initial experiments, a 1 eV gas of electrons confined in a 1.5 kG Malmberg-Penning trap will be cooled using carbon dioxide. CO_2 was chosen for initial testing because of its large ratio of inelastic to elastic scattering cross-sections in the 1 eV range. If successful, this cooling method could be used for rotating electric well confinement techniques at low axial magnetic fields. It will also be used to investigate rotating magnetic quadrupole techniques.

Preliminary result of nonneutralized two-fluid plasma experiment

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An experiment on nonneutralized two-fluid plasmas to investigate a fundamental physics of plasma rotational flow has been initiated. This study is motivated by recent theoretical works on a diamagnetic structure of magnetized plasmas with supports of strong shear flow and some two-fluid effects. In order to explore the attractive plasmas, we upgraded a small linear device and named BX-U (Beam Experiment Upgrade). BX-U is one of Malmberg type trap and equips a coaxial plasma gun at the end of the device. The goal of BX-U is to demonstrate an azimuthal ion flow perpendicular to magnetic fields under the charge nonneutral condition and reveal a possibility of high-β plasmas with especially focus on the transport phenomena related to the flow damping. As the first series of experiments, plasmas are injected into pure electron plasmas. The time history of magnetic field and electron flux of plasmas are recorded by a Hall probe and electrostatic probe, respectively. In this workshop, the preliminary result of the experiment is presented.

Formation of a Triangle Vortex Configuration Assisted by a Background Vorticity Distribution

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A vortex crystal is a quasi-stationary, symmetric array of intense vortices (clumps). The dynamics of mutually interacting point vortices has been the subject of theoretical and simulational studies of 2D turbulence. The experiment by Fine *et al.*[1] and a subsequent simulational study by Schecter *et al.*[2] were the first to reveal the important role of the interaction between the strong patches of vorticity (clumps) and the low level vorticity filling the space around the clumps in the vortical relaxation processes toward the crystal structures.

The subject of this work is to experimentally examine the contribution of a low-level of background vorticity (BGV) to the relaxation of the clumps' dynamics toward the formation of a crystal structure. To simplify the problem and quantify the degree of order, we focus on the dynamics of three clumps which are the minimum to form a unit cell in 2D crystal structures.

First, we examine the time-evolution of the triangle pattern of three clumps initially placed either in vacuum or in different levels of BGV distribution (BGVD). In vacuum, three clumps continue orbital motion with the period of $\tau_R \approx 50$ μs without showing any stationary configuration. In the presence of BGVD, on the other hand, the clumps settle down to form a symmetric triangular array.

Next, quantitative analyses are made in terms of the degree of symmetrization. The settling time to the quasi-stationary state is shorter for the higher levels of BGVD. The settling process quantified by the symmetry parameter (defined as divided area of triangle by square of its periphery) is related to the reduction of random velocities of the clumps.

Lastly we report the observation that even clumps with unequal circulations can form a symmetric cell when surrounded by unevenly-depleted zones in the BGVD. In a non-neutral plasma without counter-charge particles, only holes (density depressions) can shield, if partially, Coulomb force of clumps (regions of excessive density). The clumps generate ring holes around them and tend to partially compensate the imbalance among the circulations.

1) K. S. Fine, C. F. Driscoll, J. H. Malmberg and T. B. Mitchell, Phys. Rev. Lett. **67**, 588 (1991).

2) D. A. Schecter, D. H. E. Dubin, K. S .Fine and C. F. Driscoll, Phys. Fluids. **11**, 905 (1999).

Mechanisms of Merger and Binary Structure Formation of Two Discrete Vortices in a Nonneutral Plasma

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Abstract:

A highlight among recent experimental achievements of two-dimensional (2D) vortex dynamics using a strongly magnetized pure electron plasma is the observation of vortex crystals generated in the relaxation processes from unstable initial vorticity distributions.[1)] The role of the background vorticity distribution (BGVD) filling the space among prominent patches of vortices (clumps) was pointed out in the experiment and subsequently evaluated in its simulational analyses.[2)] BGVD was called for also in statistical derivation of the crystal distribution.[3)]

We report an experimental study focused on interaction between two clumps immersed in BGVD. Observations have shown that two clumps in BGVD merge quickly or form a binary state that lasts for a long period.[4)] Merger between clumps is a key process in vortical relaxation accompanied by reduction of number of clumps or turbulent cascade toward long wavelengths. On the other hand, processes keeping the clumps separate at a certain distance are also essential to the formation of crystal structures in quasi-steady state. The different paths of the vortical evolution critically depend on slight differences in the initial BGVD.

By a fine control of the BGVD the asymptotic inter-clump distance is found to be a two-valued function of $\nabla\zeta_b/{\zeta_b}^2$, where ζ_b is the BGV at the initial location of the clumps, corresponding to the merger and the binary state. The multiplicity is removed by considering the degree of depletion of BGVD between two clumps at the time of their proximity in the initial phase. The observations stress a dominant role which structures in BGVD play in determining the clumps' state, merger or a binary state.[5)]

1) K. S. Fine, A. C. Cass, W. G. Flynn and C. F. Driscoll, Phys. Rev. Lett. **75**, 3277 (1995).

2) D. A. Schecter, D. H. E. Dubin, K. S .Fine and C. F. Driscoll, Phys. Fluids. **11**, 905 (1999).

3) D. Z. Jin and D. H. E. Dubin, Phys. Rev. Lett. **80**, 4434 (1998).

4) Y. Kiwamoto, K. Ito, A. Sanpei, A. Mohri, T. Yuyama and T. Michishita, J. Phys. Soc. Jpn. (Lett.) **68**, 3766 (1999).

5) Y. Soga, Y. Kiwamoto, A. Sanpei and J. Aoki, submitted to Phys. Plasmas. (2003).

A new 3D PIC Code for the Simulation of the Dynamics of a Non-Neutral Plasma

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The three-dimensional evolution of a pure electron plasma trapped in a Penning-Malmberg trap or of a non-relativistic electron beam, is studied by means of a newly developed particle-in-cell code (MEP, acronym of Milano Electron Plasma). The dynamics is studied in the frame of a cold fluid, guiding center approximation. The magnetic field is assumed to be uniform along the axis of the trap. The continuity equation for the electron density is coupled to the Poisson's equation for the electrostatic potential and the equation of momentum balance along the axial coordinate. The perpendicular dynamics is described by the $\mathbf{E} \times \mathbf{B}$-drift.

The equations are discretized on a cylindrical grid, with uniform spacings in the coordinates $s \equiv r^2$, θ and z, where r is the distance from the axis of the trap, θ the azimuthal coordinate, and z the coordinate along the axis of the trap, respectively.

The equations of motion for the computational particles are written in Hamiltonian form and solved by means of a predictor-corrector symplectic scheme. The Poisson's equation is Fourier transformed both in the azimuthal and in the axial coordinate, and a three-point finite differencing is applied on a staggered grid. To solve Poisson's equation, the computational grid is duplicated in the axial direction, the system is made periodic in z, and a standard Fast Fourier Transform (FFT) is applied, so that a set of one-dimensional differential equations in the radial coordinate are solved. Inverse FFT is then applied to get the solution on the grid.

Results obtained both in the trapped plasma case and in the beam propagation regime are shown. The three-dimensional particle-in-cell code is used in particular to simulate and predict the experimental results on the dynamics of electrons obtained in the Penning-Malmberg trap ELTRAP operating at the Department of Physics of the University of Milano.